AFRL-RX-WP-JA-2015-0117

THE DUALITY OF FRACTURE BEHAVIOR IN A Ca-BASED BULK-METALLIC GLASS (POSTPRINT)

Oleg N. Senkov and Daniel B. Miracle
AFRL/RXCM

Gongyao Wang and Peter K. Liaw
The University of Tennessee

APRIL 2014
Interim Report

Distribution Statement A. Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RX-WP-JA-2015-0117 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//Signature//

MICHEAL E. BURBA, Project Engineer
Metals Branch
Structural Materials Division

//Signature//

DANIEL J. EVANS, Chief
Metals Branch
Structural Materials Division

//Signature//

ROBERT T. MARSHALL, Deputy Chief
Structural Materials Division
Materials And Manufacturing Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2014	Interim	19 March 2014 – 31 March 2014

4. TITLE AND SUBTITLE
THE DUALITY OF FRACTURE BEHAVIOR IN A Ca-BASED BULK-METALLIC GLASS (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
Oleg N. Senkov and Daniel B. Miracle - AFRL/RXCM
Gongyao Wang and Peter K. Liaw - The University of Tennessee

5d. PROJECT NUMBER
4349

5e. TASK NUMBER

5f. WORK UNIT NUMBER
X0W6

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

AFRL/RXCM
2941 Hobson Way
Bldg 654, Rm 136
Wright-Patterson AFB, OH 45433

Dept. of Material Science & Engineering
The University of Tennessee
Knoxville, TN 37996

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXCM

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-JA-2015-0117

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Journal article published in *Metallurgical and Materials Transactions A*, Volume 42A, June 2011, 1499-1503
 This report contains color. The final publication is available at DOI: 10.1007/s11661-010-0533-7.

14. ABSTRACT
$Ca_{65}Mg_{15}Zn_{20}$ bulk-metallic glass (BMG) exhibited a typical brittle fracture behavior during compressive loading at room temperature. Samples exploded into many small pieces after elastic deformation and no macroscopic plasticity was observed. The fracture surface demonstrated multiple fracture patterns, including typical metallic-glass vein patterns and glass mirror, mist, and hackle patterns. These observations show that Ca-based BMGs are subjected to multiple brittle fracture modes under compressive loading. Periodic nanoscale corrugations were found in the hackle region, which may indicate local plasticity for the brittle fracture.

15. SUBJECT TERMS
compression, fracture, bulk metallic glasses

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Micheal E. Burba
Unclassified	Unclassified	Unclassified	SAR	8	19b. TELEPHONE NUMBER *(Include Area Code)* (937) 255-9795

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

The Duality of Fracture Behavior in a Ca-based Bulk-Metallic Glass

GONGYAO WANG, PETER K. LIAW, OLEG N. SENKOV, and DANIEL B. MIRACLE

$Ca_{65}Mg_{15}Zn_{20}$ bulk-metallic glass (BMG) exhibited a typical brittle fracture behavior during compressive loading at room temperature. Samples exploded into many small pieces after elastic deformation and no macroscopic plasticity was observed. The fracture surface demonstrated multiple fracture patterns, including typical metallic-glass vein patterns and glass mirror, mist, and hackle patterns. These observations show that Ca-based BMGs are subjected to multiple brittle fracture modes under compressive loading. Periodic nanoscale corrugations were found in the hackle region, which may indicate local plasticity for the brittle fracture.

DOI: 10.1007/s11661-010-0533-7

I. INTRODUCTION

CA-BASED bulk-metallic glasses (BMGs) have a low density (~2.0 g/cm^3), low Young's modulus (~20 to 30 GPa), low shear modulus (~8 to 15 GPa), low glass-transition temperature (T_g ~373 K [100 °C] to 463 K [190 °C]), low crystallization temperature (T_x ~403 K to 513 K [130 °C to 240 °C]), and a wide super-cooled liquid temperature range ($\Delta T_{xg} = T_x - T_g \approx 30$ K [30 °C] to 80 K [80 °C]).[1–3] In addition, Ca-based BMGs have a good glass-forming ability (GFA) and are based on two simple metals—Ca and Mg.[3] Because Ca-based BMGs were synthesized successfully,[4,5] numerous Ca-based BMG systems have been discovered and studied.[6–12] The elastic modulus of Ca-based BMGs is comparable with the modulus of human bones and Ca, Mg, and Zn are biocompatible. These features make Ca-Mg-Zn-based alloys attractive for biomedical applications.[2,3,13]

Brittleness at temperatures well below T_g is a common feature of many metallic glasses, such as Zr-, Cu-, Mg-, and Fe-based BMGs.[14] Their brittleness generally is explained by limited deformation carriers that can accommodate the loading conditions, such as linear and planar defects, as well as the absence of strain hardening in amorphous structures.[15] Ca-based BMGs are extremely brittle at room temperature.[1,15,16] During compression testing of a $Ca_{65}Mg_{15}Zn_{20}$ (atomic percent) BMG, many thin pieces were observed to shed progressively from free surfaces of samples as a result of splitting fracture, which eventually exploded into numerous small pieces in the final catastrophic failure.[15,16]

GONGYAO WANG, Research Assistant, and PETER K. LIAW, Professor, are with the Department of Material Science and Engineering, The University of Tennessee, Knoxville, TN 37996. Contact e-mail: gwang@utk.edu OLEG N. SENKOV and DANIEL B. MIRACLE, Senior Scientists, are with the Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Dayton, OH 45433.
Manuscript submitted April 30, 2010.
Article published online November 12, 2010

A good understanding of the fracture behavior is critically important for the application of Ca-based BMGs. The unusual, catastrophic failure of Ca BMGs makes it difficult to study the fracture mechanisms that operate during the early stages of failure. In the current study, the fracture modes are characterized on fracture surfaces produced by interrupted compressive loading of a $Ca_{65}Mg_{15}Zn_{20}$ BMG, and the associated failure mechanisms are discussed.

II. EXPERIMENT

The $Ca_{65}Mg_{15}Zn_{20}$ (at. pct) BMG alloy was fabricated by induction melting pure elements (99.9 wt pct) in a water-cooled copper susceptor in an argon atmosphere. The prepared alloy was placed subsequently in a quartz crucible with a 2-mm diameter hole at the bottom, induction melted in an argon atmosphere, and injected into a water-cooled copper mold with a 15 mm × 15 mm × 4 mm cavity.[1,2] X-ray diffraction and differential scanning calorimetry were used to assess the structure of the 4-mm-thick plates produced. The plates were cut into 4 × 4 × 4 mm^3 samples for compression experiments. Each side of these samples was polished to a 600-SiC-grit surface finish using a polishing fixture (Model: 155, South Bay Technologies, San Clemente, CA) to keep the sides parallel and perpendicular.

A computer-controlled servohydraulic testing machine (Model: 810, MTS Systems Corporation, Eden Praire, MN) was employed to conduct the compression tests. The load frame was aligned prior to use. The compression experiments were performed at room temperature under displacement control with an initial strain rate of 10^{-4} s^{-1}. Tungsten-carbide spacers were employed above and below the specimen to prevent the deformation of the pushrods during the compression experiments. Compression loading was stopped immediately after spallation first was observed in the sample and before the catastrophic, explosive failure observed in the earlier study.[15] In general, three to four primary shear

or split fracture planes can be observed. Fracture surfaces were characterized by a Leo 1526 scanning electron microscope (SEM) (LEO Electron Microscopy Ltd., Cambridge, England) immediately after testing to avoid oxidation. Moreover, the angle between the fracture plane and the loading direction was measured.

III. RESULTS AND DISCUSSION

The plates produced were fully amorphous in the as-cast condition,[2] and detailed mechanical properties of the $Ca_{65}Mg_{15}Zn_{20}$ BMG have been reported previously.[15] The duality of fracture behavior in the Ca-based BMG, with two distinct types of fracture—shear and splitting—that have vein and conchoidal fracture morphologies, respectively, are reported in this study. A relatively flat fracture plane with a large angle of approximately 35 deg with respect to the loading axis was covered by vein patterns (Figure 1), which is the typical BMG shear-fracture feature. The vein structure has been widely observed and generally is attributed to the significant increase in the temperature in shear bands during the deformation of metallic glasses.[17,18] This feature is consistent with the reported results for many other metallic glasses, which demonstrate that the compressive fracture of metallic glasses does not occur along the plane of the maximum shear stress, and the compressive fracture angle is less than 45 deg.[19,20] Although the aspect ratio of the current sample is 1, the fracture behavior may not change with the aspect ratio when it is larger than 0.75.[21] Only specimens with the aspect ratios equal to and smaller than 0.75 exhibit an excellent compressive ductility because of the constraint on the compressive deformation of BMGs.[21] The size of vein patterns varies significantly along the perpendicular direction to the crack propagation, such as from A to B in Figure 2(a). Figure 2(b) shows the elongated cellular vein structure at high magnification. This characteristic vein in BMGs may indicate the relatively ductile local fracture.[14] Vein patterns in BMGs also seem to indicate a premelting state of the material at the shear failure surfaces. These facts indicate that the Ca-based BMG exhibits localized shear bands and local plasticity, although it lacks a global shear band and macroscopic plasticity. The width of the dimple vein structure is up to 13.2 μm in the current Ca-based BMG.

Conchoidal fracture morphologies occurred during the fracture of the $Ca_{65}Mg_{15}Zn_{20}$ BMG in the present study. Conchoidal fracture generally was found on fracture planes that locally seem to be inclined by about 0 to 20 deg to the direction of the applied load. This fracture surface produced the splitting fracture mode in the $Ca_{65}Mg_{15}Zn_{20}$ BMG.[15,16] Figure 3(a) presents the smooth mirror region near the fracture origin—the mist region, which transitions from mirror to hackle regions, and the hackle region with radiating ridges and valleys (Figure 3(b)). The smooth mirror surface produces in the initial fracture region. Then, a rougher surface

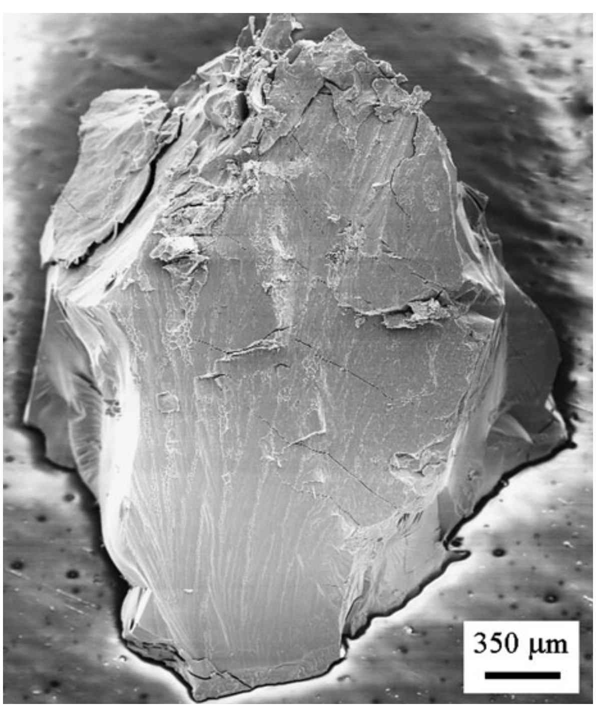

Fig. 1 The shear fracture surface of the $Ca_{65}Mg_{15}Zn_{20}$ BMG after a compression experiment.

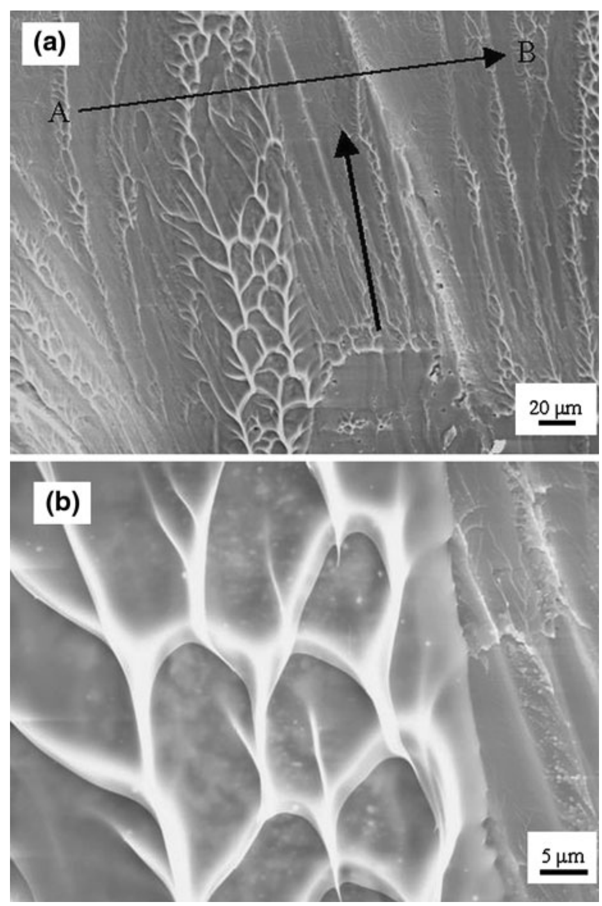

Fig. 2 Vein patterns in the shear fracture surface of the $Ca_{65}Mg_{15}Zn_{20}$ BMG after a compression experiment (*a*) at a lower magnification and (*b*) at a higher magnification. The solid arrows indicate the crack growth directions.

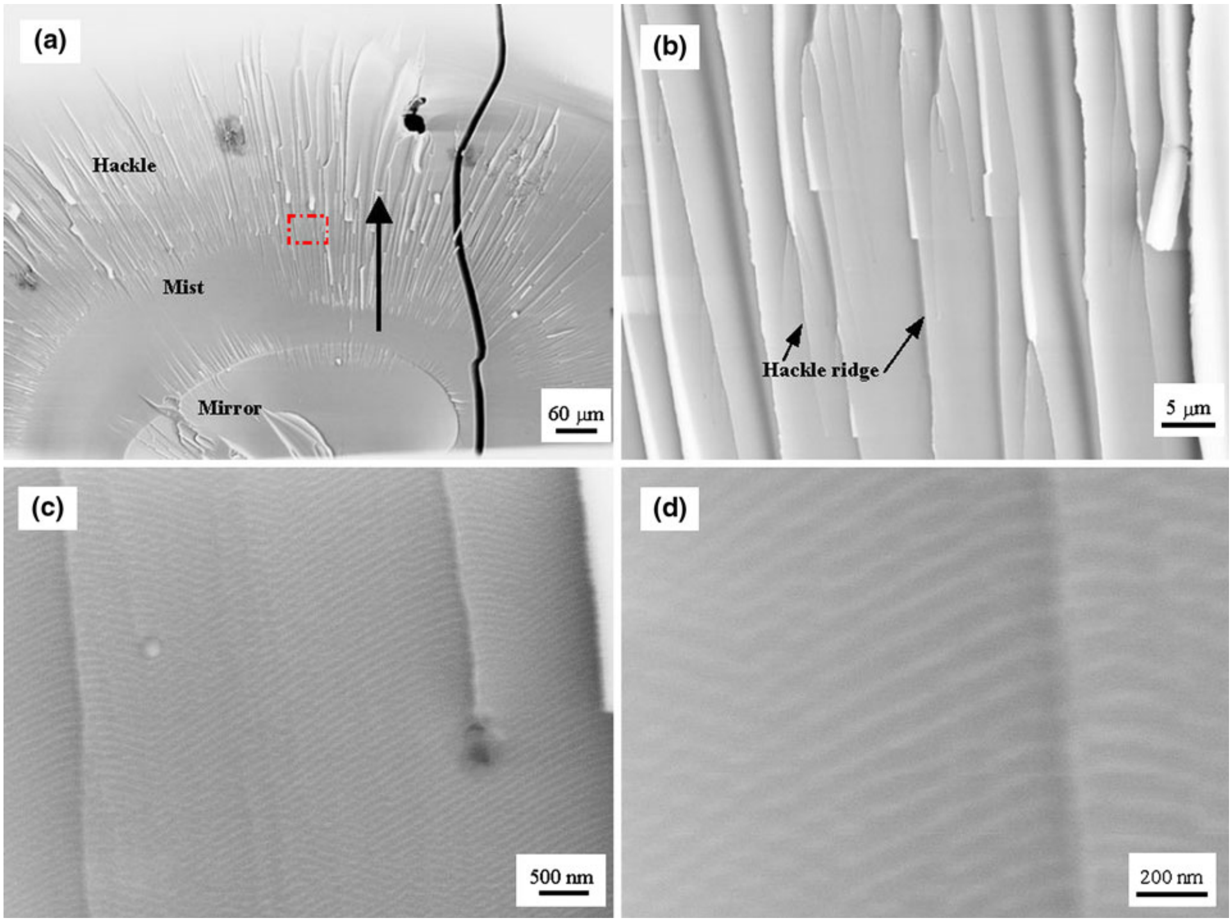

Fig. 3 Fracture surface morphology on the splitting surface of the $Ca_{65}Mg_{15}Zn_{20}$ BMG after a compression experiment. (*a*) Brittle fractography with mirror, mist, and hackle morphologies. (*b*) Detailed morphology of the hackle zone inside the box in (a). (*c*) and (*d*) show periodic corrugations at a higher magnification. The solid arrows indicate the crack growth direction.

known as mist is created when the crack accelerates and becomes unstable. Moreover, this instability eventually causes the crack to branch out, producing the roughest hackle region. The hackle region is characterized by elongated markings that emanate from the flaw origin.[22] These fracture phenomena are found in other brittle BMGs, such as Fe-based, Co-based, and Mg-based BMGs.[23–25] Zhang *et al*. reported similar cleavage-fracture morphologies on fracture surfaces from compression tests on $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_{5.5}$ and $Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$.[23] They suggest (1) that the mirror morphology forms when the propagation velocity is lower than a critical velocity, (2) that the mist region is formed as the crack front accelerates toward a critical velocity, and (3) that the hackle region is formed when the crack exceeds a critical velocity and becomes unstable. They also found periodic, wavy nanoscale steps in the mirror, mist, and hackle regions and suggested that these nanoscale steps enable the dynamic crack to dissipate more energy through a curving path.[23] Wang *et al*. found an unusual fractographic evolution from a nanoscale, dimplelike structure to nanoscale periodic steps and corrugations and then to a flat mirror zone along the crack-propagation direction when they conducted a three-point bending test on $Mg_{65}Cu_{25}Gd_{10}$ BMG.[25] They propose that the transition is caused by the propagation speed-dependent dynamic behavior of the viscoelastic matter at the crack-tip front, where local softening occurs in the fracture-process zone.[25]

In the current study, no dimple-like structure or wavy corrugations were observed in the mirror and mist regions. However, periodic, wave-like nanoscale patterns were found in the hackle region, as shown in Figures 3(c) and (d). These periodic patterns suggest that the hackle ridges formed when the crack velocity or direction varied along the crack front (Figures 3(c) and (d)).[23] In the mirror region, the crack velocity is low, and the crack front can keep the same velocity. In the hackle region, the crack velocity is fast, and the propagation is unstable. Then the hackle ridges form. Figure 3(d) demonstrated that the periodic corrugations on both sides of a hackle ridge grew in different directions with asynchronous steps. The wavelength of the periodic corrugations is measured to approximately 76 nm. The periodic nanoscale corrugations may result from a local plastic fracture, and the local plasticity plays a dominant role at the front of the crack tip.[26] However, these fine nanoscale patterns may reflect the relatively brittle fracture in BMGs.

The large-scale vein patterns and fine-scale wavy corrugations could be two indicators of the local

ductility in the Ca-based BMG. In the present investigation, the vein patterns might result from the shear fracture through shear bands, which generally were observed in Zr and Cu-based BMGs, and the wavy corrugations were the results of splitting fracture through the crack-tip opening, which usually was found in Fe- and Co-based BMGs. However, these two fracture modes on the same sample have not been reported yet. This trend may indicate that the Ca-based BMG demonstrates different fracture characteristics. The Ca-based BMG has better local ductility under a shear-fracture mode than that under a splitting-fracture mode. Xi *et al.* found that the plastic-process zone w (measured as the average width of the dimple or the wavelength of the vein features) increased linearly with the increase of $(K_C/\sigma_Y)^2$ where K_C is the fracture toughness and σ_Y is the fracture strength.[27] We assume that the current Ca-based BMG follows the same trend. The average of σ_Y is about 364 MPa.[15] For the shear mode of the Ca-based BMG, w is up to 13.2 μm (estimated from the width of the dimple vein structure) and K_C is estimated to be ~8.79 MPa·m$^{0.5}$. For a splitting mode of the Ca-based BMG, w is 76 nm (estimated from the wavelength of the periodic steps/corrugations) and K_C of the Ca-based BMG is estimated to be ~0.75 MPa·m$^{0.5}$. Although the fracture toughness of the Ca-based BMG under shear mode can reach 8.79 MPa·m$^{0.5}$, the Ca-based BMG only exhibited small fracture toughness for splitting mode, which is comparable with the silicate glasses, with K_C ~0.68 to 0.91 MPa·m$^{0.5}$.[27] This finding may suggest that the brittleness of the Ca-based BMG is close to common oxide glasses. Thus, the Ca-based BMG demonstrates two types of fracture behavior under the compression loading. In fact, the Poisson's ratio of the $Ca_{65}Mg_{15}Zn_{20}$ BMG is ~0.3.[3] In general, metallic glasses with a Poisson's ratio less than 0.31 to 0.32 are more brittle.[28] Therefore, the current Ca-based BMG is in the transition from "brittle" to "ductile" characteristics. In addition, according to the classical nucleation theory, the viscosity in the supercooled liquid is a key parameter to influence the glass-forming ability of metallic glasses. Thus, the viscosity of the glass-forming liquids could help to understand the room-temperature mechanical properties. In general, The temperature dependence of the viscosity is reflected in a fragility index ($m = d\log \eta/d(T_g/T)|_{T\quad T_g}$).[29] Some researchers found that Poisson's ratio (and ductility) increases,[29 31] whereas the GFA decreases[32,33] with the increase of m. Ca-based BMGs generally show a low m value[30,34] as well as a good GFA. This fact also indicates that the Ca-based BMGs could exhibit the brittleness. The continued investigation on the brittle/ductile fracture behavior of the Ca-based BMGs may provide an opportunity to understand the brittleness nature of BMGs thoroughly.

IV. CONCLUSIONS

The $Ca_{65}Mg_{15}Zn_{20}$ BMG exhibited the duality of fracture behavior under compression loading. SEM observation showed that the fracture surfaces contained the typical BMG vein pattern in the shear-fracture mode as well as the typical glass mirror, mist, and hackle patterns in the splitting/opening fracture mode. Furthermore, periodic nanoscale corrugations were found in the hackle region, which may indicate a local plasticity for the brittle fracture. Ca-based BMGs could be an ideal material for studying the brittle/ductile fracture mechanism in metallic glasses.

ACKNOWLEDGMENTS

We would like to acknowledge the financial support of the National Science Foundation, including the following: (1) the Division of the Design, Manufacture, and Industrial Innovation Program, under Grant No. DMI-9724476; (2) the Combined Research-Curriculum Development Programs, under EEC-9527527 and EEC-0203415; (3) the Integrative Graduate Education and Research Training Program, under DGE-9987548; (4) the International Materials Institutes Program, under DMR-0231320; (5) the Major Research Instrumentation Program, under DMR-0421219; (6) the Division of Civil, Mechanical, Manufacture, and Innovation Program, under CMMI-0900271; and (7) the Materials World Network Program, under DMR-00909037, with Ms. M. Poats, and Drs. C.V. Hartesveldt, D. Dutta, P.W. Jennings, L.S. Goldberg, L. Clesceri, C. Huber, C.E. Bouldin, Dr. C.V. Cooper, and Dr. A. Ardell as contract monitors. Work at the Air Force Research Laboratory (AFRL) was conducted through the AFRL on-site contract No. FA8650-04-D-5233 and through an AFOSR Task (01ML05-COR, Dr. J. Fuller, Program Manager).

REFERENCES

1. O.N. Senkov, D.B. Miracle, and J.M. Scott: *Intermetallics*, 2006, vol. 14, pp. 1055 60.
2. M.L. Morrison, R.A. Buchanan, O.N. Senkov, D.B Miracle, and P.K. Liaw: *Metall. Mater. Trans. A*, 2006, vol. 37A, pp. 1239 45.
3. O.N. Senkov, D.B. Miracle, V. Keppens, and P.K. Liaw: *Metall. Mater. Trans. A*, 2008, vol. 39A, pp. 1888 1900.
4. K. Amiya and A. Inoue: *Mater. Trans. JIM*, 2002, vol. 43, pp. 81 84.
5. K. Amiya and A. Inoue: *Mater. Trans. JIM*, 2002, vol. 43, pp. 2578 81.
6. O.N. Senkov and J.M. Scott: *Mater. Lett.*, 2004, vol. 58, pp. 1375 78.
7. O.N. Senkov and J.M. Scott: *Scripta Mater.*, 2004, vol. 50, pp. 449 52.
8. F.Q. Guo, S.J. Poon, and G.J. Shiflet: *Appl. Phys. Lett.*, 2004, vol. 84, pp. 37 39.
9. O.N. Senkov and J.M. Scott: *J. Non Cryst. Sol.*, 2005, vol. 351, pp. 3087 94.
10. E.S. Park, W.T. Kim, and D.H. Kim: *Mater. Sci. Forum*, 2005, vol. 475 9, pp. 3415 18.
11. O.N. Senkov, J.M. Scott, and D.B. Miracle: *J. Alloys Comp.*, 2006, vol. 424, pp. 394 99.
12. S. Gorsse, G. Orveillon, O.N. Senkov, and D.B. Miracle: *Phys. Rev. B*, 2006, vol. 73, pp. 224202 9.
13. M.D. Demetriou, A. Wiest, D.C. Hofmann, W.L. Johnson, B. Han, N. Wolfson, G.Y. Wang, and P.K. Liaw: *JOM*, 2010, vol. 62, pp. 83 91.
14. C.A. Schuh, T.C. Hufnagel, and U. Ramamurty: *Acta Mater.*, 2007, vol. 55, pp. 4067 4109.

15. G.Y. Wang, P.K. Liaw, O.N. Senkov, D.B. Miracle, and M.L. Morrison: *Adv. Eng. Mater*., 2009, vol. 11, pp. 27 34.
16. J. Raphael, G.Y. Wang, P.K.. Liaw, O.N. Senkov, and D.B. Miracle: *Metall. Mater. Trans. A*, 2010, vol. 41A, pp. 1775 79.
17. J.J. Lewandowski and A.L. Greer: *Nat. Mater*., 2006, vol. 5, pp. 15 18.
18. B. Yang, C.T. Liu, T.G. Nieh, M.L. Morrison, P.K. Liaw, and R.A. Buchanan: *J. Mater. Res*., 2006, vol. 21, pp. 915 22.
19. Z.F. Zhang, J. Eckert, and L. Schultz: *Acta Mater*., 2003, vol. 51, pp. 1167 79.
20. H. Li, C. Fan, K. Tao, H. Choo, and P.K. Liaw: *Adv. Mater*., 2006, vol. 18, pp. 752 54.
21. W.H. Jiang, G.J. Fan, H. Choo, and P.K. Liaw: *Mater. Lett*., 2006, vol. 60, pp. 3537 40.
22. J.J. Mecholsky, S.W. Freiman, and R.W. Rice: *J. Mater. Sci*., 1976, vol. 11, pp. 1310 19.
23. Z.F. Zhang, F.F. Wu, W. Gao, J. Tan, Z.G. Wang, M. Stoica, J. Das, J. Eckert, B.L. Shen, and A. Inoue: *Appl. Phys. Lett*., 2006, vol. 89, pp. 251917 3.
24. G. Wang, Y.T. Wang, Y.H. Liu, M.X. Pan, D.Q. Zhao, and W.H. Wang: *Appl. Phys. Lett*., 2006, vol. 89, pp. 121909 3.
25. G. Wang, Y.N. Han, X.H. Xu, F.J. Ke, B.S. Han, and W.H. Wang: *J. Appl. Phys*., 2008, vol. 103, pp. 093520 2.
26. G. Wang, D.Q. Zhao, H.Y. Bai, M.X. Pan, A.L. Xia, B.S. Han, X. K. Xi, Y. Wu, and W.H. Wang: *Phys. Rev. Lett*., 2007, vol. 98, pp. 235501 4.
27. X.K. Xi, D.Q. Zhao, M.X. Pan, W.H. Wang, Y. Wu, and J.J. Lewandowski: *Phys. Rev. Lett*., 2005, vol. 94, pp. 125510 4.
28. J.J. Lewandowski, W.H. Wang, and A.L. Greer: *Phil. Mag. Lett*., 2005, vol. 85, pp. 77 87.
29. V.N. Novikov and A.P. Sokolov: *Phys. Rev. B*, 2006, vol. 74, pp. 0642031 7.
30. E. Pineda, Y. Zhang, and A.L. Greer: *J. Alloys Comp*., 2007, vol. 434 5, pp. 145 48.
31. E.S. Park, J.H. Na, and D.H. Kim: *Appl. Phys. Lett*., 2007, vol. 91, pp. 031907 3.
32. O.N. Senkov: *Phys. Rev. B*, 2007, vol. 76, pp. 104202 6.
33. G.J. Fan, J.F. Loffler, R.K. Wunderlich, and H.J. Fecht: *Acta Mater*., 2004, vol. 52, pp. 667 74.
34. O.N. Senkov and D.B. Miracle: *Metall. Mater. Trans. A*, 2010, vol. 41, pp. 1677 84.